Exploring the underlying mechanism of LURR theory

- Reorientation of stress as a possible mechanism of LURR

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Abstract

In this paper, we study the likelihood that LURR (Load-Unload Response Ratio) shares common underlying mechanism with the accelerating moment release (AMR) phenomenon. Previous studies using Australian and Chinese earthquake data showed a correlation between earthquake magnitude and the "Critical Region" size for LURR (radius that maximizes the LURR peak preceding an earthquake) similar to that found for the critical region size for AMR. Here we analyse data from the last five major earthquakes in California and find that the LURR peaks become progressively higher as the radius is decreased. These results suggest that the crust nearer to the epicenter is closer to a critical state as based on the LURR criterion. Hence, we suggest that the critical region concept in AMR in which there is a correlation between the critical region size and earthquake magnitude may not apply to LURR in California. We also examined the dependence of LURR on assumed principle press direction and found the LURR anomaly could be maximized by selecting a different principle stress direction for each earthquake. We conjecture that in a fault system with numerous randomly oriented small faults, a "phase up" process prior to the main shock may occur in which stress orientation becomes more coherent such that faults along a particular direction become increasingly vulnerable to failure relative to those along other directions resulting in LURR becoming high in this direction. This direction may be different from that predicted by principle stress directions specified on regional stress maps and may change from time to time, causing the most vulnerable orientation of small faults to swing back and forth. The differing patterns of LURR change with assumed principle stress direction in California and Australia seems to support this argument. The stress reorientation process represents a possible mechanism to explain the LURR observations using the current implementation in multi-fault regions.

Introduction

Load/Unload Response Ratio (LURR) theory is an earthquake prediction method developed by Yin and co-workers (Yin et al, 1991; 1995; 2000) that aims at intermediate-term prediction of earthquakes. It is based on the notion that a physical system such as a block of the Earth's crust will show significantly different response to external loading than unloading prior to the failure (or instability) of the system, while no such difference exists during the stable phase. If such a difference (precursor) could be detected, an intermediate-term prediction could be made for the upcoming major earthquake in that region.

Accelerating seismic moment release (AMR) has also been proposed as an intermediate-term precursor (Bufe et al, 1993) and as observational evidence in support of the Critical Point Hypothesis for earthquakes (Sornette et al, 1995) Recent work using Australian and Chinese data showed a similar scaling between earthquake magnitude and critical region size calculated using AMR and LURR (Yin et al, 2002) suggesting a common underlying physical mechanism. Here we analyse California data where catalogs are expected to be more complete. In past studies of AMR, the presumed critical region size has been calculated as the radius around the epicentre that minimizes the curvature parameter ***c*** = (RMS error power law fit)/(RMS error linear fit) of the cumulative Benioff strain release. For the 5 major earthquakes in California since 1980, Bowman (Bowman et al, 1998) found critical region radii between 110km to 200km. His argument based on that dataset on the relationship between critical region size and the magnitude of ensuing earthquake is not entirely convincing because of the intrinsic limitation of curve–fitting, although subsequent work compiling results from many regions provides support for a clear correlation albeit with significant scatter (e.g. Jaumé, 1999; Wang et al, 2002). The reliability of using the radius that minimizes the curvature parameter ***c*** is questionable when one considers the intrinsic limitations of the data and of curve fitting. Taking the highly focused Kern County Earthquake as example, the Bowman paper indicates a critical region size of 325 km but at a radius of less than 200 km, there is not enough seismicity to obtain a statistically significant curve-fit. Hence, it is possible that the AMR critical region size predicted by curve fitting is less than 200 km but that this was not detected in this case due to data limitations.

Definition of LURR

LURR was originally defined in differential form (Yin & Yin, 1991), making it a state variable depending only on the state of the system at that moment. In practice, however, we have no means to measure the instantaneous strain of a large block of the Earth's crust in response to tectonic loading stress. Instead, the observable seismic energy release of small earthquakes is selected as the response measure. Since energy release is the accumulative effect of loading over a long time interval, we replace the loading increment with the loading duration and introduce the integral form of LURR.

$$Y = \frac{X_+}{X_-} = \frac{\frac{1}{T_+}\sum_{t\in T_+} E(t)}{\frac{1}{T_-}\sum_{t\in T_-} E(t)} = \frac{T_-}{T_+}\cdot\frac{\left(\sum_{i=1}^{N^+} E_i^m\right)_+}{\left(\sum_{i=1}^{N^-} E_i^m\right)_-}, \quad (1)$$

where the "+" sign means loading and the "–" means unloading as determined by the change in Coulomb Failure Stress (CFS) due to Earth tides. The numerator and denominator denote the average energy release during the loading and unloading duration respectively and E is calculated using the formula $\log E = a + bM$. The exponent m can be chosen as m=0, 1/3, 1/2, 2/3 or 1. When m=1, E^m is corresponds to energy and when m=1/2, E^m denotes the Benioff strain.

However, the sacrifice of the compromise to the integral definition is that the calculation may be influenced by other factors not related to the original principle behind LURR in ways yet unknown. Specifically, LURR according to the integral definition is related to the history of system evolution and is thus dependent of many extrinsic parameters, such as magnitude range, the region size, fault direction, etc. For example, when defining effective CFS for criteria of load/unload, we define it either as that on the fault plane of ensuing main shock or that on an assumed fault plane determined by the tectonic pressure axis direction. In the former case, not all the earthquakes would have occurred on the main fault plane (or parallel faults); while in the latter, it has been shown that the tectonic stress changes direction prior to and after a major earthquake (Zhao D., 1998). In either case, the choice of CFS is ambiguous. A better choice would be to compute the fault plane for each small earthquake and to calculate CFS accordingly but data is generally not sufficient to allow this approach in practice.

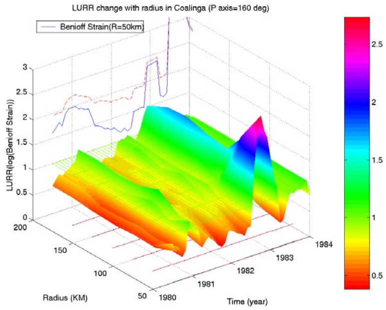
Since LURR is an averaged variable, random factors are inevitably involved causing LURR to fluctuate around unity with the fluctuation magnitude depending on the number of events used to calculate LURR. We therefore define a threshold above which the LURR value is considered significant rather than a random disturbance. This threshold is indicated by statistically simulated LURR results under a specified confidence limit (Zhuang and Yin, 2000). In this paper, we simply state that if there is any LURR value higher than the simulated LURR anomaly with 90% confidence (noted as Y_{90}) within 2 years prior to the main shock, it will be considered as significant (i.e. as a precursor). Hence LURR hereinafter is defined as $Y' = Y/Y_{90}$, where $Y' > 1$ means significant anomaly.

Dependence of LURR on region size

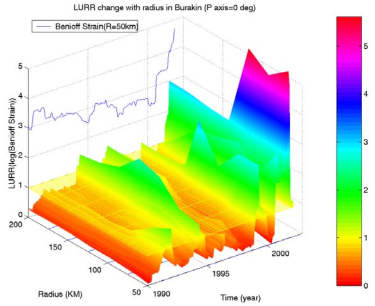
Now we examine the dependence of LURR on region size (radius around the epicenter) in order to determine if there is a particular radius when LURR reaches a peak.

We focus our study on last five major earthquakes in California with magnitude greater than 6.5 between 32° N and 40°N latitude (table below) since 1980. The Council of the National Seismic System (CNSS) Worldwide Earthquake Catalog is used, which is accessible via the Internet at the Northern California Earthquake Data Center (http://quake.geo.berkeley.edu/cnss).

A typical LURR evolution with time for different region size is shown in Figure 1a where the LURR calculations used a time window length of one year, magnitude range from 0 to 4.0, and assumed tectonic press in direction of N160°.



a. Coalinga, California.



b. Burakin, West Australia

Fig. 1: The LURR evolution for different region sizes. The cutoff at smaller radii is due to insufficient data (less than 20 events in a time window).

Figure 1a shows that for the Coalinga area, the LURR anomaly increases in magnitude as the radius is decreased. Table 1 summarizes results for all five earthquakes analysed and indicates the LURR anomaly increases with decreasing radius for each of these earthquakes. In each case, the radius that maximized LURR was the smallest radius where there was "sufficient data" (more than 20 events in a time window) to calculate LURR.

Position	**Date**	**M**	**Radius by AMR**	**Radius by LURR**
Coalinga	02/05/1983	6.7	175±10 km	50km
Superstition	24/11/1987	6.6	275±95 km	25km
Loma Prieta	18/10/1989	7.0	200±30 km	25km
Landers	28/06/1992	7.3	150±15 km	25km
Northridge	17/01/1994	6.7	73±17 km	25km

Table 1: LURR critical region size results compared to AMR results of Bowman et al, 1998.

Two earthquakes in Australia were analysed previously and showed LURR critical region size correlating with AMR critical region size (Yin et al, 2000). Here we analysed one additional earthquake. Figure 1b is an example from Burakin, West Australia, where a series of M>5.0 earthquakes occurred since late 2001 till early 2002 and suggests the LURR critical region size is around 100 km, consistent with the previous study of Yin et al and the AMR critical region size – magnitude scaling relation.

How can the different results between California and Australia be explained? Two possible answers are:

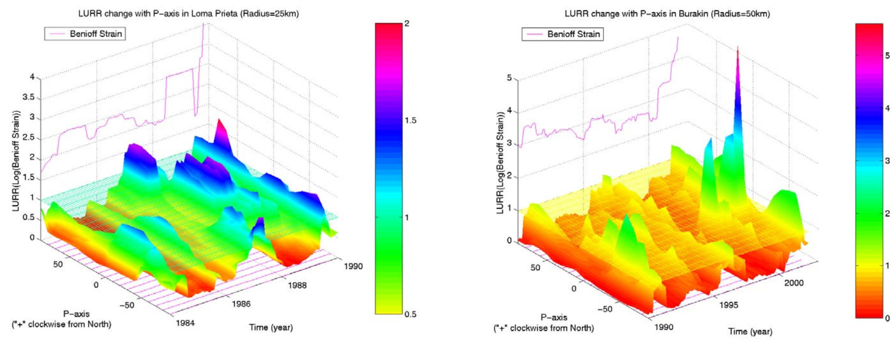
(1) Either the method used to calculate the critical region size for LURR is not applicable in California; or

(2) There is no LURR "critical region" for California data so the crust becomes increasingly sensitive to LURR (closer to a critical state) closer to the epicentre.

Re-orientation of stress by activity on small faults as a possible mechanism of the current LURR implementation

Some researchers found that the tectonic stress field rotates before and after the major earthquakes in California (Zhao et al, 1998). In order to study the relation between stress rotation and LURR, we compute LURR based on CFS calculations assuming different tectonic pressure axes (P-axis).

Figure 2a is a typical example of LURR variation with P-axis direction from –90° (West) clockwise to +90°(East). From the results, it is evident that LURR patterns as a function of P-axis in some regions vary in time (peaks occur in different directions at different times) while for other regions the LURR patterns undergo minimal time variation. We conjecture that this time variability, when it occurs, is related to tectonic stress rotation. According to Zhao D. (Zhao, D. et al, 1998), a temporal rotation of the crustal stress field in the Northridge area occurred before and after the 1994 earthquake.



a. Loma Prieta, California.

b. Burakin, West Australia.

Fig.2: LURR vs. tectonic pressure axis (P-axis) direction.

In Burakin, West Australia, however, LURR has peaks only in direction along the North-South direction (Figure 2b), as if the tectonic stress field remains fixed in this direction for a long time. This may be the result of the relatively stable tectonic stress field in Australian plate.

The different pattern of LURR anomalies in California and Australia suggests a hypothesis: When the crust is far from criticality, the stress will be highly heterogeneous allowing small faults with random orientations to break resulting in LURR calculated in any fixed direction fluctuating around unity. But when the crust becomes close to failure, stress will become reoriented in a particular direction determined by the external tectonic stress so ruptures for a particular fault orientation will become dominant, causing LURR along this direction to become higher. The proposed reorientation of the stress such that the principle stress direction become more coherent in the vicinity of the epicenter can be compared to the postulated growth in correlation lengths for the Critical Point Hypothesis for earthquakes. However, the difference in critical region sizes based on LURR and AMR in California suggest that despite this comparison, there are substantial differences between the AMR and LURR mechanisms.

Summary

The method to identify critical region size in AMR doesn't seem to apply to LURR for interplate data from California. Using a dataset of five large recent California earthquakes, the LURR peak progressively increases as the region size is decreased. In contrast, previous studies using Australian and Chinese data indicated the critical region size to magnitude scaling relation for LURR and AMR was identical. Furthermore, in the California data, LURR analysis suggests an evolution in principle stress orientation whereas no such evolution effect is observed for Australian data.

We conclude that it is possible LURR does not share a common underlying mechanism with AMR (at least in California), but may be caused by critical sensitivity which is reached by a "phase up" effect as randomly oriented small fractures rupture, causing a reorientation of the principle stress towards a certain direction determined by tectonic stress prior to main shock, resulting in higher LURR in this direction. Such a re-orientation process represents a possible underlying mechanism for the LURR phenomenon in its current implementation for multi-fault regions.

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